Quantification of methane and nitrous oxide emissions from Borgstedt waste treatment facility, Germany

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Quantification of methane and nitrous oxide emissions from Borgstedt waste treatment facility, Germany

Borgstedt waste treatment facility, June 2014.

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1. Introduction and objective

According to the current EU waste policy as stated by the waste hierarchy ideally waste generation should be prevented, what cannot be prevented should be prepared for re-use, recycling, recovering (with priority given to material recovery followed by energy recovery) and as a final option landfilled (Directive 2008/98/EC, article 4, 2008). Diverting specific waste streams from the waste hierarchy should be justified by lifecycle thinking on the overall environmental impacts of the generation and management of such waste. The European waste framework directive set goal for recycling of household waste of 50% by 2020 (Directive 2008/98/EC, article 11, 2008). Specifically concerning biowaste EU Member States shall take measures to encourage: (a) the separate collection of bio-waste for e.g. composting and anaerobic digestion; (b) the treatment of bio-waste in a way that fulfils a high level of environmental protection; and (c) the use of environmentally safe materials produced from bio-waste (Directive 2000/60/EC, article 22, 2000). In Denmark, most of the biowaste is instead incinerated in "state-of-the-art" waste-to-energy plants substituting the use of fossil fuels but losing important materials and substances including nitrogen and phosphorous. However, in other European countries such as Germany a significant part of the biowaste is separately collected and recycled. Common treatment options for biowaste in the European Union (EU) include aerobic composting, anaerobic digestion or a combination of those. In compositing the organic material is stabilized and sanitized producing compost, which is beneficial to plant growth. In anaerobic digestion a part of the organic carbon is converted to biogas, which can be used to produce electricity and heat. Also a digestate is produced, which like compost can be used on land to support plant growth. In the future the amount of biowaste treated by biological processes is expected to increase in order to recycle the carbon and the nutrients in the waste material.

Biological treatment of organic wastes however entails the production of various gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO) and ammonia (NH_3). Some of these gases are classified as greenhouse gases (GHGs), thus contributing to climate change. Currently, only very few GHG emission data from biological treatment facilities are available. Recent emission measurements performed at a number of Danish landfills with on-site treatment facilities for biowaste have shown significant methane emissions from facilities treating biowaste such as garden/park waste in open windrows (Mønster el al, 2014b; Andersen et al., 2010). The magnitude of these GHG emissions may significantly impact the overall environmental performance of the treatment plant. The dynamic and diffuse nature of GHG gas production and emission from full scale treatment facilities challenge the quantification of these emissions.

The Technical University of Denmark has recently implemented a novel analytical setup enabling mobile measurements of small (ppb level) changes in atmospheric methane, nitrous oxide and ammonia concentrations. This enables detection and quantification of methane, nitrous oxide and ammonia sources by performing measurements downwind from the source in combination with release and measurement of a tracer gas. The analytical setup and the dynamic tracer dispersion method has since November 2011 been tested at more than 18 Danish landfills since, 3 composting plants, 5 wastewater treatment plants and one biogas

facility, building up a sound knowledge on quantification of the fugitive methane emission from full-scale facilities.

The objective of this study was to quantify methane, nitrous oxide and ammonia emissions from a waste treatment facility plant in Northern Germany receiving biowaste using the mobile tracer dispersion method. Emission factors were estimated relating the measured emissions to the waste material treated and to the compost and methane gas generated.

2. Plant description

Borgstedt is a combined biogas and composting facility that annually treats about 45,000 tonnes of source segregated organic household waste. The waste is received in a hall where it is stored shortly prior to treatment. The received waste is either fed into one of 10 anaerobic digestion reactors (30,000 tonnes) or to one of 7 aerobic degradation reactors (15,000 tonnes). The latter is due to current under capacity at the plant. The waste is in both cases not pretreated before entering the reactors. In the anaerobic reactor, the waste material is sprinkled with water. The leachate from the waste material is recirculated. The temperature in the anaerobic reactor is about 38 °C. The residence time in the anaerobic digestion is between 4 and 6 weeks depending on different factors like the biogas production. The biogas is mainly produced inside the anaerobic reactors and is collected and burned in a biogas engine on-site producing electricity and heat. After the anaerobic digestion, the wet digestate is mixed with fresh organic waste before entering the aerobic reactors. In the aerobic reactors the mixture is aerated to ensure aerobic conditions and therefore a quick composting is achieved within a residence time of 5 to 7 days. The excess air is collected and sent to a biofilter. After the aerobic reactors the material is laid out in windrows (40 meters long, 5 meters wide at the bottom and 3 meters high) for sanitation and maturation. The windrows are turned twice a week with a windrow compost turner until the compost is mature (about 8 weeks, while being turned twice per week), where it is then sieved into compost and residues. The turning procedure takes about 1½ hours. The compost is stored in an open hall until it is sold to farmers and private households and the residues are landfilled in accordance with German law. Figure 1 shows an overview of the plant.

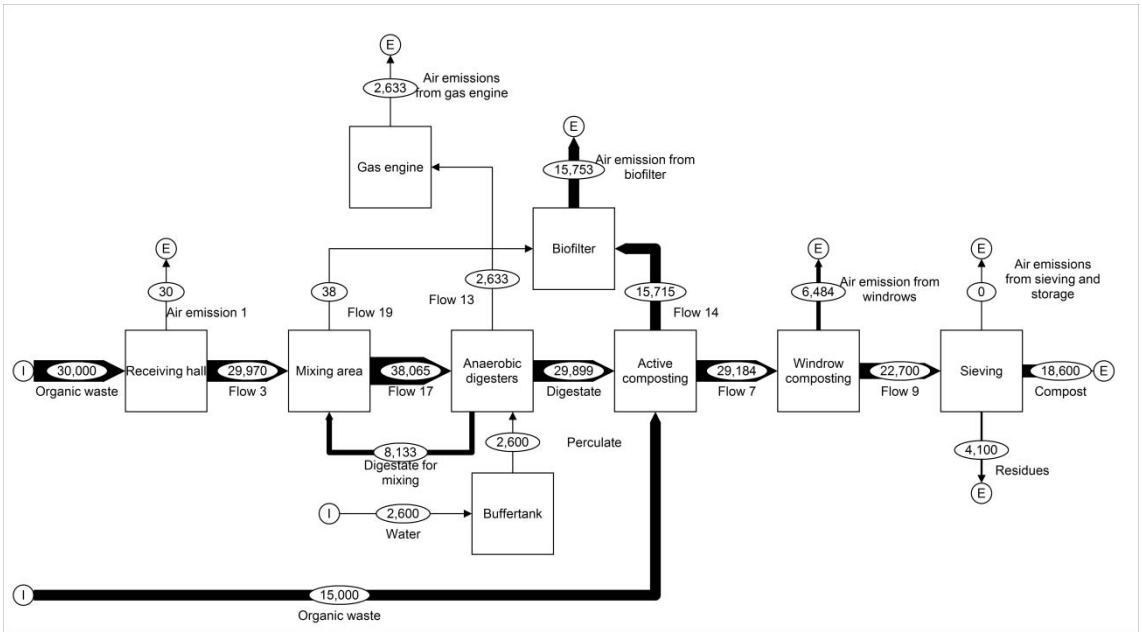

Figure 1. Flow diagram of Borgstedt.

In 2014, the production was 18,600 tonnes of compost, 4,100 tonnes of residues, 4,780 MWh of heat and 4,550 MWh of electricity. About 1.012 MWh of the heat generated is used for district heating. The biogas production was 2.28 million m^3 biogas with a methane content of 58% vol. The electricity was sold to the grid and 15 % of the heat was used for internal heat and by surrounding industries.

3. Description of the dynamic tracer dispersion method and the analytical platform

Total emissions of methane and nitrous oxide were quantified using a mobile tracer dispersion method that combines a controlled release of tracer gas from the biogas and composting plant with concentration measurements downwind of the plant, by using a mobile high-resolution analytical instrument (Börjesson et al., 2009, 2007; Galle et al., 2001; Scheutz et al., 2011). The method has been used successfully in the last few decades, and with new developments in analytical technology it has become a powerful tool for quantifying methane emissions from landfills (Mønster et al., 2014; 2015) and more recently methane and nitrous oxide from waste water treatment plants (Yoshida et al., 2014). The tracer dispersion method in general is based on the assumption that a tracer gas released at an emission source, in this case a biogas and composting plant, will disperse into the atmosphere in the same way as methane emitted from the plant. Assuming that the wind direction is defined, the conditions in the air above the plant are sufficiently mixed for the methane and tracer gas to be fully mixed, and the tracer gas release is constant, the methane emission rate (E_{gas}) can be calculated as a function of the ratio of the integrated cross-plume concentration of methane emitted to the integrated cross-plume concentration of the tracer gas, as follows:

$$E_{target\ gas} = Q_{tracer} \cdot \frac{\int_{plume\ start}^{plume\ end}(C_{target\ gas} - C_{target\ gas\ background})dx}{\int_{plume\ start}^{plume\ end}(C_{tracer} - C_{tracer\ background})dx} \cdot \frac{MW_{target\ gas}}{MW_{tracer}}$$

where Q_{tracer} is the release rate of the tracer gas (kg/h), C_{gas} and C_{tracer} denote cross-plume concentrations (ppbv) above the background, MW denotes molecular weight and x corresponds to distance across the plume (between 200 and 900 m for all cross-plumes in this report). The principle is shown in Figure 2.

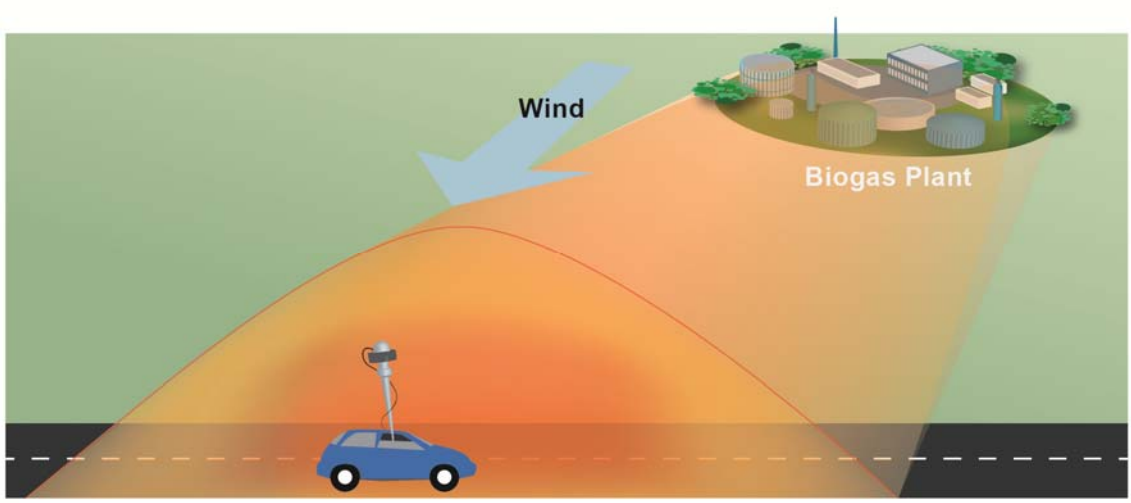

Figure 2. The principle of the dynamic plume method for quantifying greenhouse gas emissions from fugitive sources.

The measurements were conducted by driving through the downwind N_2O, CH_4, and tracer gas (C_2H_2) plumes multiple times. The plumes were integrated for each measurement sweep, giving a real-time, plant integrated emission rate for the duration of the plume traverse. Two mobile measurement devices were used for the detection of atmospheric concentrations downwind from the sources. Both instruments were based on cavity ring-down spectroscopy (CRDS), an optical technology in which the direct measurement of infrared absorption loss in a sample cell is used to quantify the mole fraction of the gas. One instrument was equipped with lasers, to detect CH_4 and C_2H_2 (G2203, Picarro, Inc., Santa Clara, CA), and another to detect $N_2O/NH_3/H_2O$ (S/N JADS2001, Picarro, Inc., Santa Clara, CA). Two separate lasers are used in these spectrometers - one to measure N_2O and the other to measure NH_3 and H_2O. Light from each laser, tuned to specific near-infrared absorption for the targeted analyte molecules, is directed sequentially into an optical resonator known as an 'optical cavity', which consists of a closed chamber with three highly reflective mirrors and serves as a compact flow cell with a volume of less than 10 standard cm^3 into which the sample gas is introduced. The flow cell has an effective optical path length of 15-20 km, and this long path length allows for highly precise measurements (with ppb or even parts-per-trillion uncertainty, depending on the analyte gas), using compact and extremely reliable near-infrared laser sources. Gas temperature and pressure are controlled rigidly in these instruments (Crosson 2008), and this stability allows the instrument (when properly calibrated to traceable reference standards) to deliver accurate measurements that need very infrequent calibrations relative to other $N_2O/NH_3/H_2O$ instrumentation. A further description of the equipment is presented in Mønster et al. (2014) and in Yoshida et al. (2014).

Both instruments were connected to a GPS, which recorded the geographical location of each atmospheric concentration measurement with a positioning accuracy of 20 cm. Temperature, atmospheric pressure, and wind speed and direction were recorded simultaneously by a mobile weather station. The air intake of the mobile sampling device was set above ground at 2 m. To obtain the best possible simulation, tracer gas was released at the part of the biogas and composting plant where the main parts for the greenhouse gasses were being emitted. Initial measurements on and around the plant were conducted for locating these emission areas/processes.

4. Description of measurement campaigns.

Measurements were performed from June 4th to June 6th, 2014. Table 1 shows an overview of the measurement campaigns performed including information on weather conditions (temperature, wind direction and speed), tracer gas release (number of release points and total release rate), and plume traverses (measuring distance and number of traverses).

On June 4th in the afternoon, an initial screening measurement campaign for methane and nitrous oxide in the area surrounding the waste treatment facility were conducted with the purpose to identify other emission sources, which could interfere with the plume measurements from the treatment facility. Combined with on-site screening, optimal placement of the tracer gas was determined in order to get the best simulation of the emissions from the facility. The screening campaign was followed by a tracer gas release campaign. One tracer gas cylinder was used to simulate the emissions from the facility. The tracer gas release rate was 0.65 kg h^{-1} released from one gas cylinder. Figure 3 shows the placement of the tracer gas cylinders. The temperature was 17-21 °C with an atmospheric pressure between 1009 and 1011 mbar and wind with from east-northeast (4-5 m s^{-1}) enabling downwind measurement at a road 1600-1800 m west of the facility (see Figure 4). Seven successful traverses were performed between 17h50 and 18h40.

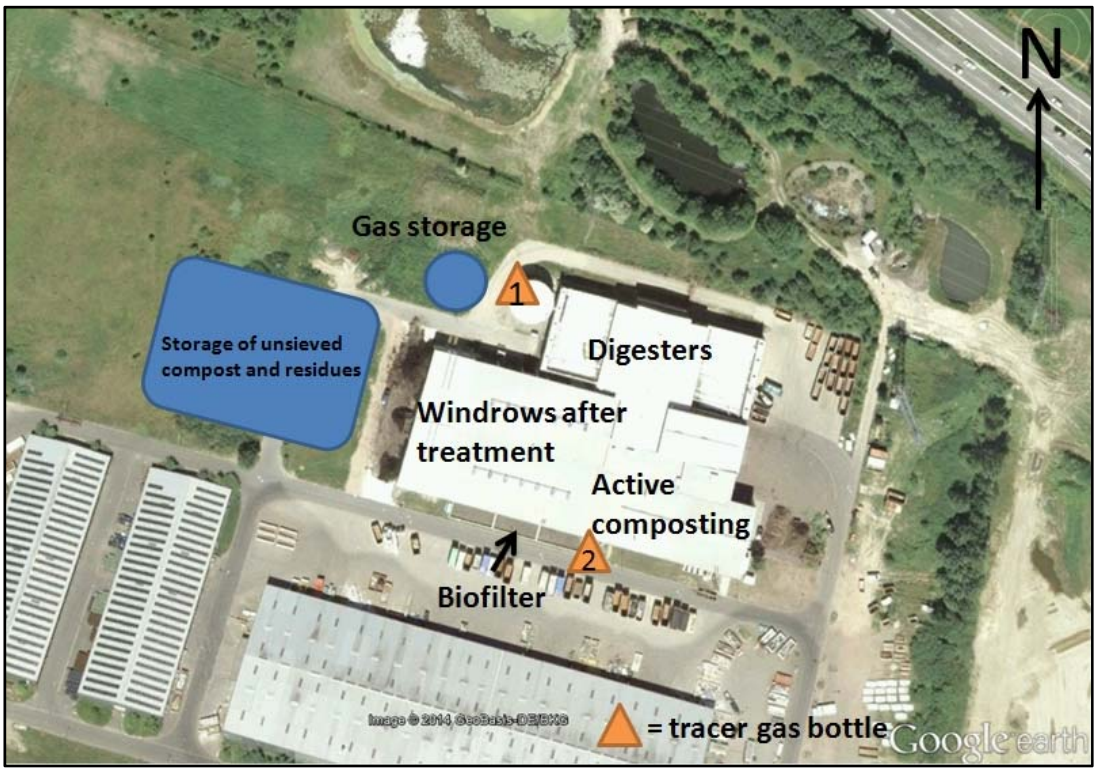

Figure 3. Overview of the waste treatment facility. The Google Earth picture is from year 2000 where some of the unit processes were not build. These have been marked with blue in the figure. The orange triangles mark the tracer gas placement on June 4th (tracer 1), June 5th (tracer 1 & 2) and June 6th (tracer 1 & 2).

On June 5th, the temperature varied between 16 and 21 °C and the atmospheric pressure was between 1008 and 1010 mbar. The wind had a speed of 4-7 m s^{-1} coming from southwest making is possible to measure the downwind plume at two distances (800 and 1600 m) northeast of the facility (see Figure 4). Two tracer gas bottles were used and placed at the same locations as on the first measurement day (see Figure 3). The total tracer gas release rate was 1.30 kg h^{-1} (0.65 kg h^{-1} per gas cylinder). In total, 30 traverses were performed between 11h10 and 18h00 at the two distances approximately 800 and 1600 m from the facility. Additionally, direct measurements from the surface of a large biofilter were done as well as at individual waste treatment processes (this is explained in section 5.2).

On June 6th, the temperature was between 17-22 °C and the atmospheric pressure varied between 1011 and 1014 mbar. The wind speed was 3-5 m s^{-1} from south-southwest allowing downwind measurements on the road just on the other side of the motorway, 400-500 m north-northeast of the facility. Two tracer gas bottles were placed the same place as on June 5th and 43 traverses were performed between 10h40 and 14h45, where some of them enabled a quantification of the emission from the individual areas where the tracer gas bottles were placed. On June 6th, the windrows were mechanically turned, starting at 12h50 and lasting to 14h20.

Table 1. Measurement details from the measurement campaigns.

Date	Measuring time interval	Wind speed (m s^{-1}) and direction	Atmospheric pressure (mbar)	Tempe-rature (°C)	Total tracer gas release rate (kg h^{-1}) and tracer release points (*n*)	Measuring distance (m)	Plume traver ses
June 4th	17:50-18:40	4-5, ENE	1009-1011	17-21	0.65 (*1*)	1600-1800	7
June 5th	11:15-13:30 17:00-18:00	4-7, SW	1008-1010	16-21	1.30 (*2*) 1.30 (*2*)	800 1600	24 6
June 6th	10:40-12:45 12:45-14:25 14:25-14:45	3-5, SSW	1011-1014	17-22	1.30 (*2*)	400-500	21 19 3

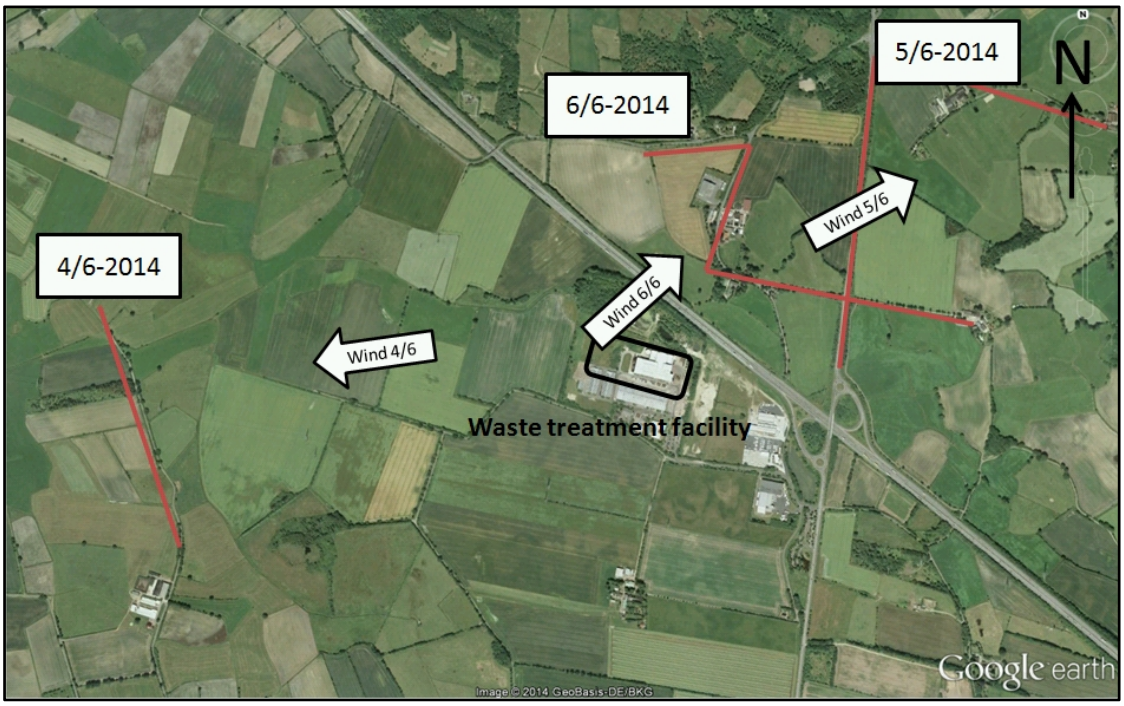

Figure 4. The roads used for measurement of the downwind plume the three days of the three measurement campaigns.

5. Results & Discussion

5.1 Screening of the area around the waste treatment facility

Initially a screening measurement campaign of the area around the waste treatment facility was conducted in order to identify potential methane and nitrous oxide sources, which could cause interference with the plume measurements from the waste treatment facility. The screening campaign was done on June 4th. Besides Borgstedt, sources of methane were found at a farm 600 m north-northeast from the waste treatment facility. This farm had an anaerobic digester for biogas production, which resulted in fugitive methane emissions. Further northeast was another farm, which had smaller methane emissions, probably from a manure tank at the farm. Figure 5 shows measurements done on June 5th where tracer gas and wind direction could be used to

illustrate the individual methane sources and the possibility to separate them from the methane emission from the waste treatment facility.

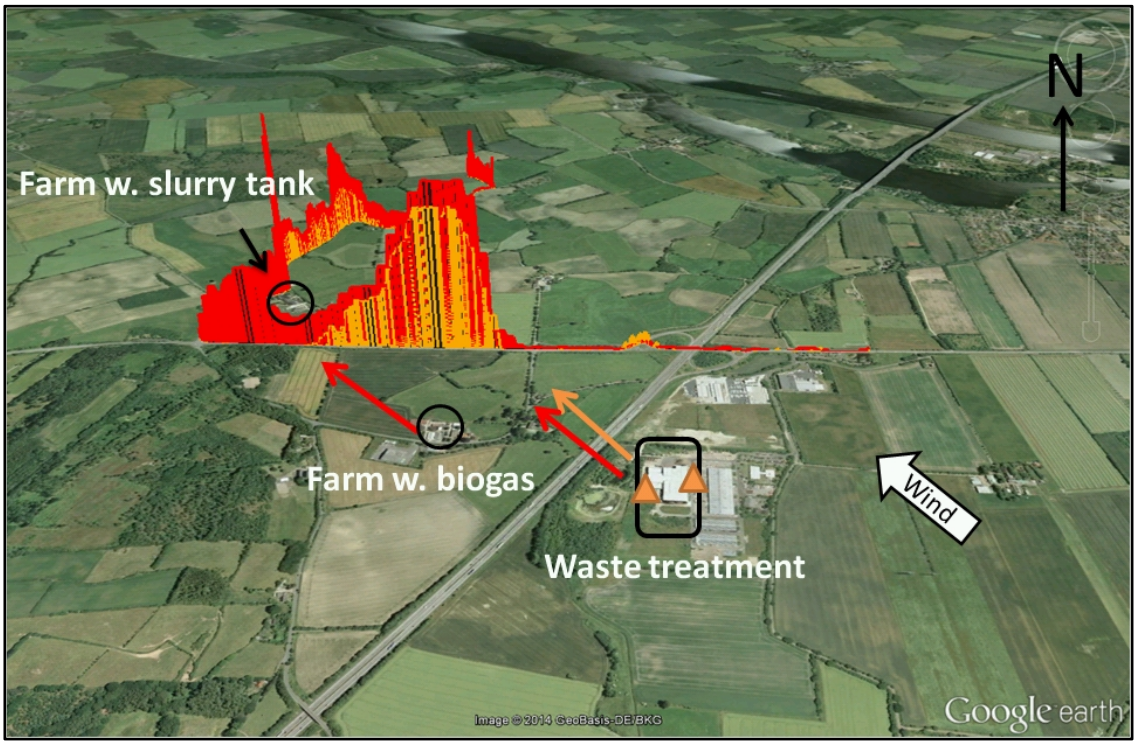

Figure 5. Downwind plumes of methane and tracer gas from the waste treatment facility and the methane plumes from two farms near the facility. Background concentrations are subtracted and concentrations are multiplied for better visual experience. Maximum methane concentrations above background were 100 ppb and 220 ppb downwind of the farm and the waste treatment plant, respectively.

5.2 Initial on-site screening of Borgstedt

An initial screening for methane and nitrous oxide at Borgstedt was done prior to placing the tracer gas bottles for quantifying the whole site emission. Figure 6 shows the relative methane and nitrous oxide concentrations above background around the waste treatment facility. The measurements showed that the main emissions of both methane and nitrous oxide came from inside the building i.e. compost windrows, aerobic composting reactors and anaerobic digester reactors.

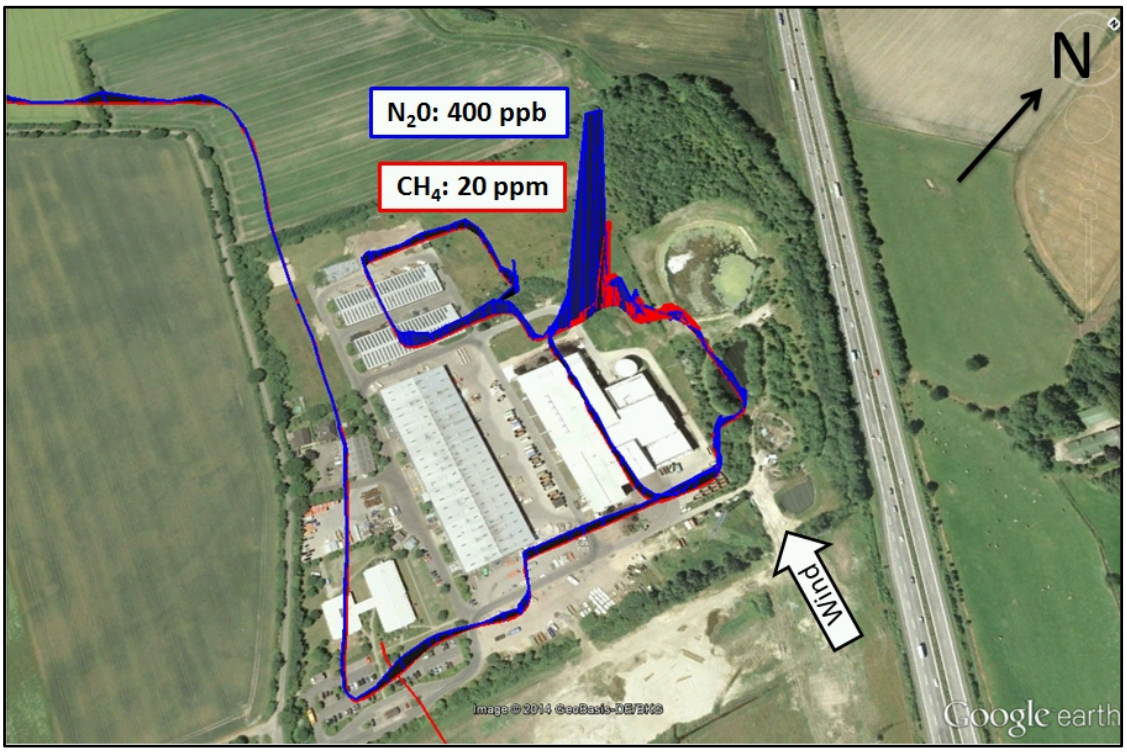

Figure 6. Relative methane and nitrous oxide concentrations above background concentrations during screening on Borgstedt. Maximum concentrations measured above background are marked in the figure. Maximum concentrations were 20 ppm and 400 ppb for methane and nitrous oxide, respectively. Note: The GPS had an issue and all measurements the first 2 hours on June 4th are "moved" approximately 50 m north. Map: Google, Aerodata International Surveys.

Direct measurements at the biofilter on June 5th (see Figure 7) showed highly elevated concentrations of methane, nitrous oxide and ammonia. The maximum air concentrations of methane and nitrous oxide were around 20 ppm and 400 ppb, respectively. The ammonia concentration was out of range for the analytical instrument (which is 35 ppm), as it is build for trace gas measurements. The CH_4/N_2O ratio based on the air concentrations measured above the biofilter was approximately 16.

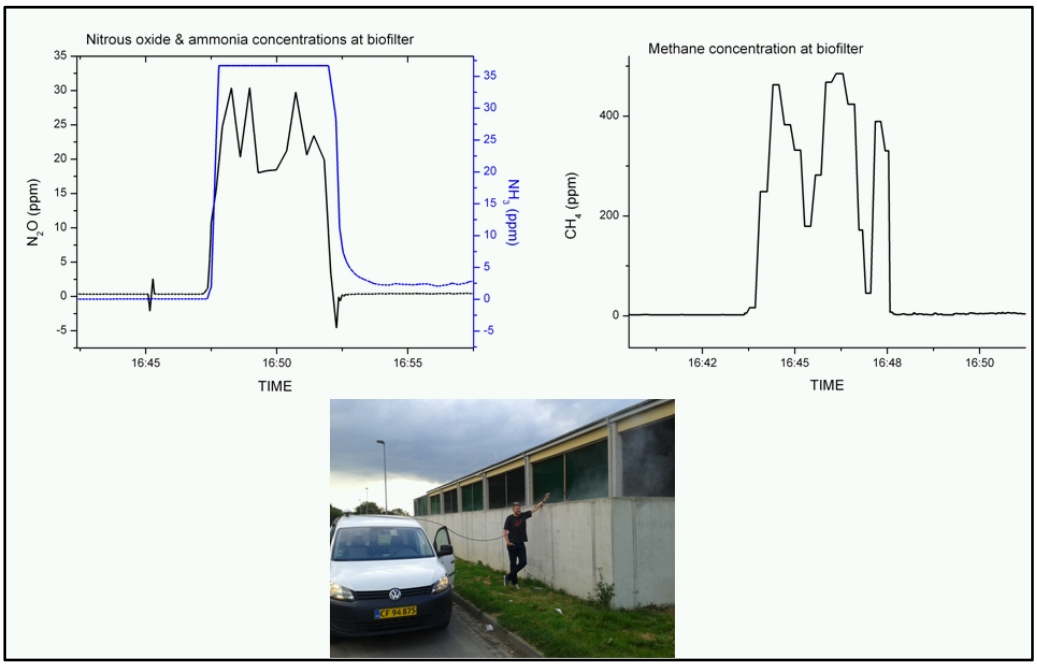

Figure 7. Direct air concentration measurements at the biofilter. Nitrous oxide and methane concentrations were in the range of 30 ppm and 470 ppm, while the ammonia concentration was too high (>35 ppm) for the analytical equipment.

Direct measurements inside the main building of the waste treatment facility showed different concentrations at the different unit operations. Figure 8 shows the concentration of methane at the different operations and Table 2 shows the measured concentrations above background.

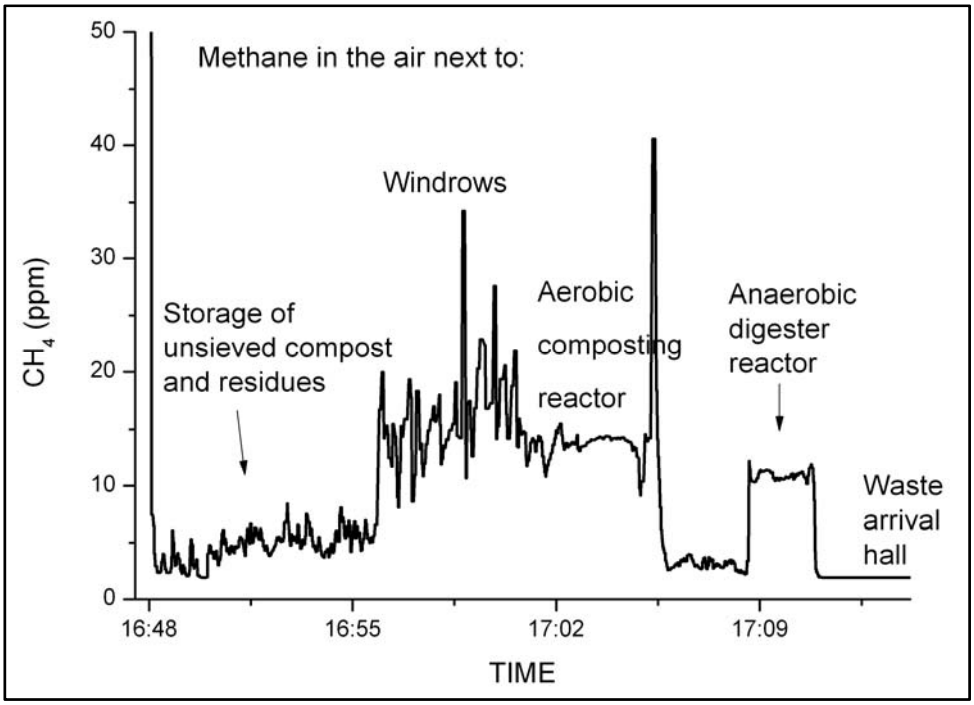

Figure 8. Methane concentrations during a slow drive through the waste treatment facility.

Table 2. Average atmospheric concentrations above background concentration measured while driving slowly through the waste treatment facility passing the different waste treatment processes.

Process	CH_4 (ppm)	N_2O (ppm)	NH_3 (ppm)
Waste arrival hall	<0.1	-	-
Aerobic composting reactor	12.3	0.3	4.9
Anaerobic digester reactor	8.6	0.2	1.6
Windrows	13.5	0.1	2.6
Storage of unsieved compost and residues	3.8	0.1	2.4

5.3 Whole facility emissions

Even though that the direct measurements showed emission of nitrous oxide and ammonia from the waste treatment facility especially from the biofilter and windrows, these emissions were too small for downwind plume measurements. However, it was possible to measure downwind plumes of methane and an estimate of the emission rates of nitrous oxide and ammonia could be obtained by combining the gas ratios from the direct measurements performed at windrows and biofilter with the calculated emission rate for methane and assuming a constant emission ratio of methane, nitrous oxide and ammonia.

The waste treatment consists of several unit operations and the whole site quantification conducted far away from the facility was unable to quantify the emissions from the individual unit operations. However, based on the measurements performed on June 6th on the road 400-500 m north-northeast of the facility it was possible to separate the emissions from the two areas each represented by the two tracer gas cylinders thereby quantify the emission from these two areas (see Figure 9).

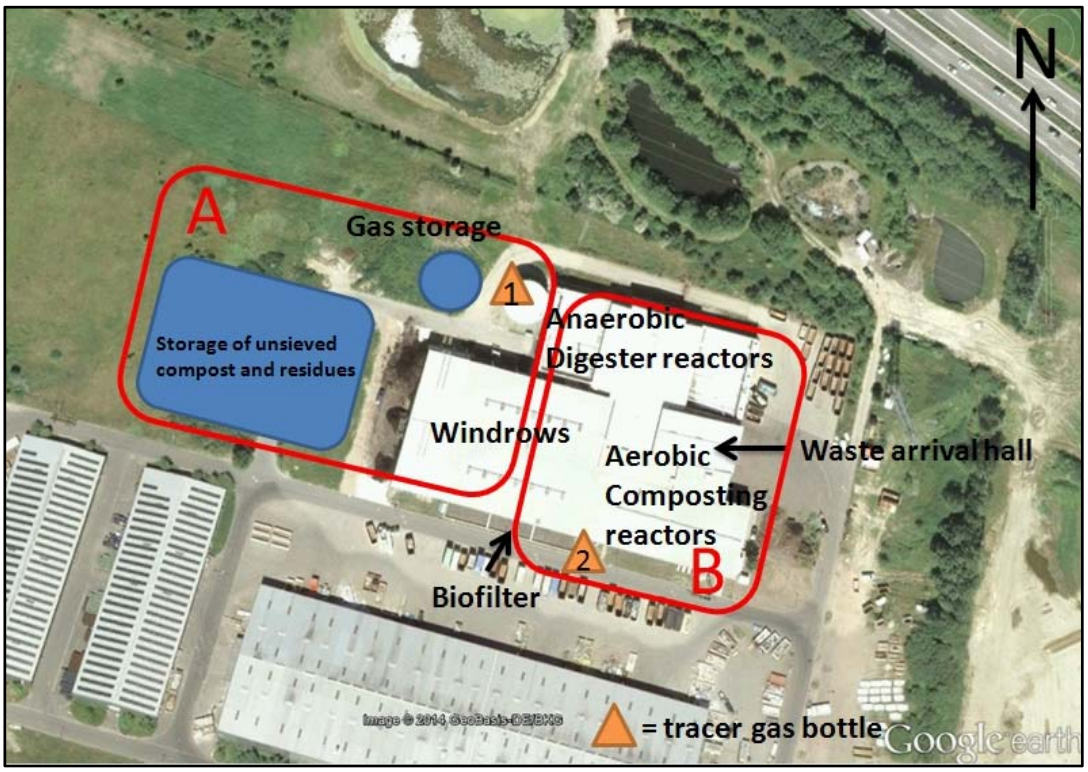

Figure 9. The approximate areas A and B where the two locations for tracer gas release simulated the methane emission on June 6th.

Emission quantifications were done on all three days. On June 4th, the wind enabled plume traverses west from the facility. Table 3 shows the calculated emissions during the approximately half hour from 18:00 to 18.30 where plume traverses were successful conducted. The activities at the plant were at a minimum level, the workers had gone home, and only the biological processes were running. Front loaders and drum sieves were shut down. The only unusual thing was that the gate between the hall with the aerobic composting reactors and the area with the compost windrows were left open. The average methane emission was 27.5 kg h^{-1} with a standard deviation (SD) of 7.4 kg h^{-1} and a standard error (SE) on the mean value of 2.8 kg h^{-1}. The average emission ± SD is the interval of where the next measurement (with 66% certainty) will be within and the average ± SE is the interval where the "true" emission rate is within (with 66% certainty).

Table 3. Calculated emissions obtained from traverses done on June 4th.

Time	Emission (kg CH_4 h^{-1})
17.59	23.6
18.06	21.8
18.10	26.2
18.17	24.2
18.21	38.3
18.25	37.8
18.31	20.6
Average	**27.5**
Std dev	**7.4**
Std err	**2.8**

On June 5th when the wind had changed approximately 180 degrees, the downwind plumes were measured from around 11.00 until 13.30 and again from 17.00 to 18.00. Unfortunately, many of the plume traverses conducted during the last hour were not useful, as it was not possible to separate the methane plume from the facility from other interfering sources. Figure 10 shows a plot of the methane and tracer gas concentration in a typical traverse measured 800 m downwind the facility. The first methane and tracer plume represents the emission from the waste treatment facility while the second methane plume (where there is no tracer) represents emissions from a nearby farm. With this wind direction, it was possible to separate the two plumes and the emission from the facility could be quantified.

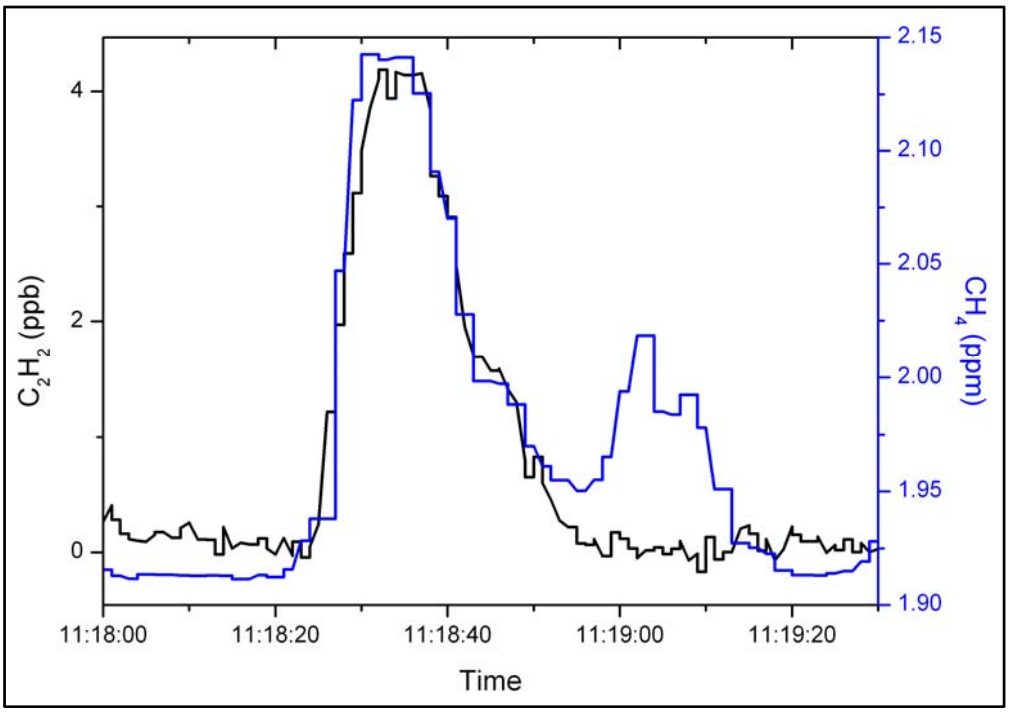

Figure 10. Methane and tracer gas concentrations above background measured on June 5th approximately 700 m downwind from the waste treatment facility. The data are the same as the closest plumes shown in Figure 4, and show the separation of methane from the waste treatment and from the farm producing biogas.

The methane emission rates calculated from the individual traverses measured on June 5th are shown in Table 4 and the average emission throughout the whole measurement day was 28.5 kg CH_4 h^{-1} with SD and SE of 6.1 and 1.1 kg CH_4 h^{-1}. The average emission rate during the first measurement period (11.00 to 13.30), when there were activities (such as receiving of waste, emptying and filling of reactors both anaerobic and aerobic, drum sieving) at the facility, was 30.2 kg CH_4 h^{-1} with SD of 5.2 and SE of 1.1 kg CH_4 h^{-1}, while the later (17.00 to 18.00) when the facility was working on a minimum emission rate was 21.5 kg CH_4 h^{-1} with SD of 4.2 and SE of 1.7 kg CH_4 h^{-1}. The higher methane emission 27.5 kg CH_4 h^{-1} measured after ended working hours the day before (June 4th) could be a result of that the door between the windrow composting area and the hall with the aerobic reactors were left open, which was not the case on June 5th.

Table 4. Calculated emissions obtained from traverses done on June 5th.

Time	Time	Emission (kg CH_4 h^{-1})	Emission (kg CH_4 h^{-1})
First measuring period	**11.19**	24.0	30.2±5.2[a]
	11.21	27.0	
	11.27	27.6	
	11.30	28.8	
	11.33	29.2	
	11.38	24.9	
	11.42	26.6	
	11.44	33.2	
	11.47	20.2	
	11.48	36.0	
	11.59	29.3	
	12.39	25.8	
	12.44	29.9	
	12.47	31.3	
	12.51	33.9	
	12.53	36.6	
	12.59	44.4	
	13.01	35.9	
	13.06	32.1	
	13.08	33.3	
	13.14	28.9	
	13.17	28.8	
	13.20	23.7	
	13.25	34.3	
Second measuring period	**17.01**	22.6	21.5±4.2[a]
	17.03	25.7	
	17.06	22.0	
	17.13	17.8	
	17.18	15.2	
	17.58	25.6	
Average	**Average**	**28.5**	
Std dev	**Std dev**	**6.1**	
Std err	**Std err**	**1.1**	

[a] SD

On June 6th, the wind directions enabled a long time series without interfering methane sources and some of the traverses were able split up the emission contribution from the two areas that the tracer gas releases were imitating the methane emission. Area A represents the storage area of the final compost only covered by a roof, the gas storage and the semi-open building with windrow composting of digested and aerated waste material from the reactors. Area B represents the area with the anaerobic reactors and the aeration reactors, where the off-gas is treated in a biofilters also located in this area.

Measurements were done for four hours between 10.45 and 14.45. At around 12.48, the windrows were mechanically turned. A total of seven turnings were done corresponding to one turning of each of the seven windrows at the plant during the measurement period. The time of the turnings are shown in Table 5. Note that the emissions from the turning have to reach the instrumentation before they are measured hence a delay from the turning times to the measurement times by the measurement distance divided by the wind speed, thus a delay of approximately 2 minutes.

Table 5. A total of seven turnings were done corresponding to the seven windrows at the plant during the measurement campaign. The turnings took place at the following times. Note that the emissions from the turning have to reach the instrumentation before they are measured hence a delay from the turning times to the measurement times:

# Turning	Start	Finish
1	12.48	13.00
2	13.04	13.13
3	13.17	13.26
4	13.30	13.39
5	13.43	13.53
6	13.55	14.09
7	14.11	14.22

Table 6 shows the methane emissions measured during the four hour period. The emissions measured between approximately 12.50 and 14.24 were measured during mechanically turning of the windrows.

The average total emission for the four hour period (10.45 and 14.45) was 31.1 kg CH_4 h^{-1} with SD 11.4 and SE 1.7 kg CH_4 h^{-1}.

The average emission during the first part without windrow turning (10.40 to 12.50) was 26.3±5.5 kg CH_4 h^{-1} whereas it was 36.4±14.7 kg CH_4 h^{-1} during the second part (12.50 to 14.24) with windrow turning. After tuning (14.24-14.45) the emission was 19.1±0.9 kg CH_4 h^{-1}. The increased emission during the windrow turning was most like due to increased release of methane stored inside windrows as the material is lifted and turned. However, during the period with turning, both higher and lower emissions were observed. The high emissions most likely represented turning events, whereas the lower emissions represented the period between the seven individual turnings. The lower emission measured after the turning event is likely due to that most of the gases were released during the turning and the production of new methane takes time.

Two plumes (13.11 & 13.33) measured during windrow turning, could be separated into area A and B. The highest emissions were obtained from the area A with the windrows, and thus confirmed that the emission increase indeed came from turning of the windrows. Including only emissions measured without windrow turning, the plumes where source area quantification were possible showed that 69% of the methane was emitted from area A (Compost, windrows & gas storage) and 31% from Area B (biofilter).

Table 6. Calculated emissions obtained from traverses done on June 6th. The period with turning of the windrows is marked by gray. The arrival of the emission at the measuring transect is delayed about two minutes from the release time. The time interval where emissions during turning can be expected to show up at the measuring road is therefor 12:50 to 14:24.

Time	Total Emission (kg CH_4 h^{-1})	Average total emission (kg CH_4 h^{-1})	Emission area A (incl. area with windrows) (kg CH_4 h^{-1})	Emission area B (kg CH_4 h^{-1})
10.47	26.5	No windrow turning: 26.3±5.5[a]		
11.01	18.5			
11.05	26.4			
11.10	30.5			
11.12	34.7			
11.17	19.0			
11.20	21.2			
11.23	23.3			
11.27	36.8			
11.32	34.9			
11.41	26.8			
11.44	34.0			
11.52	20.2			
12.01	23.8			
12.13	29.3			
12.17	21.4			
12.23	26.6		17.2	9.4
12.29	21.2		16.9	4.3
12.36	22.2		16.6	5.6
12.40	25.7		17.7	8.0
12.44	30.2			
12.49	31.5	Windrow turning: 36.4±14.7[a]		
12.55	36.1			
12.59	58.9			
13.09	37.7			
13.13	31.3			
13.11	65.4		54.5	9.6
13.29	16.0			
13.33	55.5		41.4	14.1
13.39	61.5			
13.42	18.8			
13.49	42.0			
13.54	28.5			
14.00	33.5			
14.04	41.0			
14.07	37.4			
14.11	23.0			
14.15	25.2			
14.18	20.3		13.0	7.3
14.25	28.4			
14.28	18.3	No windrow		

14.34	18.9	turning: 19.1±0.9[a]		
14.39	20.0		12.9	7.1
Average	**30.1**		**23.8**	**8.2**
Std dev	**11.4**		**15.4**	**3.0**
Std err	**1.7**		**5.5**	**1.1**

[a] SD

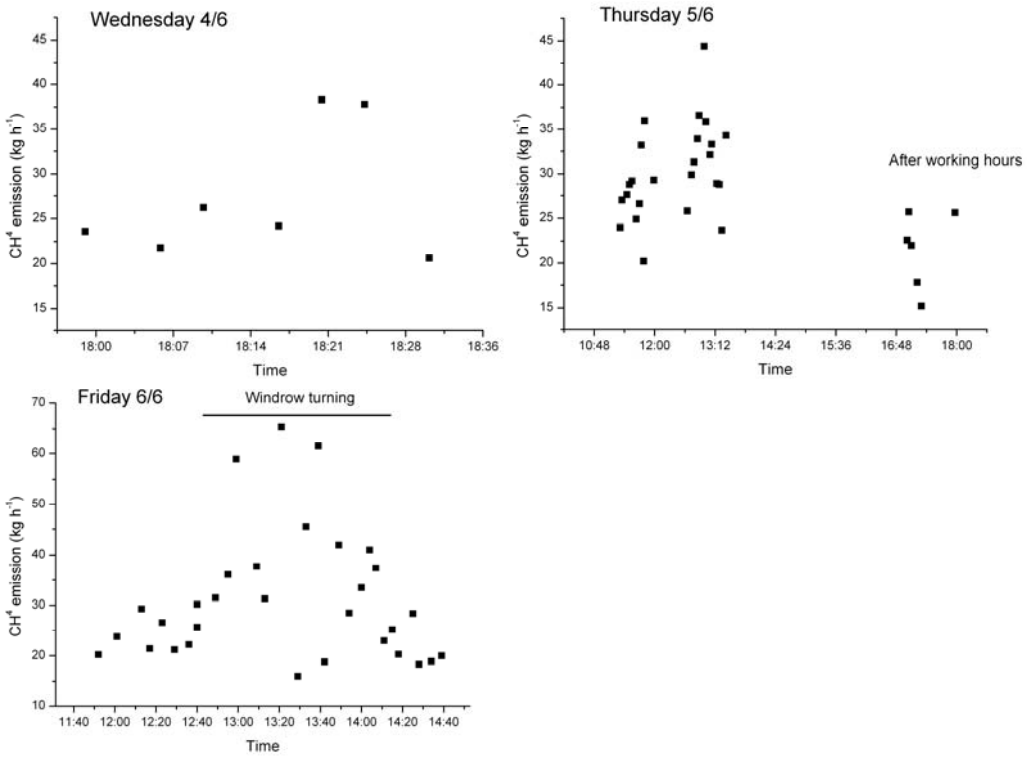

Figure 11. Time series of the methane emission rate at the three measurement days.

Estimation of N_2O and NH_3 emissions from on-site sources

Area B including the anaerobic and aerobic reactors, the waste arrival hall and the biofilter.

The methane emission from the biofilter was found from plume measurements on Friday 6/6. A split-up of the plumes from the A and B areas were possible at eight plumes and the average methane emission from the eight plumes was 8.2 kg CH_4 h^{-1}. The direct measurements at the biofilter showed a CH_4/N_2O ratio of 16 (volume/volume), which gives an emission of N_2O from the biofilter of: $E(N_2O)$ = 8.2 kg CH_4 h^{-1} x (44/16) /16 = 1.4 kg N_2O h^{-1}, assuming all methane measured from the B area were emitted from the biofilter. The ammonia concentration from the biofilter was higher than the maximum range of the instrument (35 ppm), which results in the ratio $CH_4/NH_3 < 0.85$ or an ammonia emission of: $E(NH_3) > 8.2$ kg CH_4 h^{-1} x (17/16) /0.85 > 10.3 kg NH_3 h^{-1}, also assuming that all the measured methane in the downwind plume was emitted from the biofilter.

Area A including the windrows, gas storage and storage for unsieved compost.

The nitrous oxide and ammonia concentration ratios at area A were lower than the concentrations measured at the biofilter. The CH_4/N_2O ratio was 38 at the unsieved compost and 135 at the windrows. Although the eight downwind plumes that could be separated into A and B area showed that approximately 69% of the CH_4 emission happened from area A, a significantly smaller part of the N_2O emission originates from here. The individual N_2O emission contribution to the different sources at area A could not be measured. The methane emission from the A area (23.8 kg h^{-1}, measured from the eight plumes that could be separated) combined with the measured N_2O concentration emission from the area gives an estimated emission of 0.3 to 0.6 kg N_2O h^{-1}. The CH_4/NH_3 ratio was 1.6 and 5.2 at the compost and the windrows giving an estimated NH_3 emission between 3 and 10 kg NH_3 h^{-1} from area A.

Daily emission averages and emission factors.

Based on the three measuring campaigns a daily average emission rate was calculated. The calculation considered the emissions measured during the open hours of the plants as well as the emissions measured when the plant was closed and there were no activities on-site. The average methane emission during opening hours was ((32.2+26.3+35.9+19.1)/4 =) 27.9 kg CH_4 h^{-1} whereas the average methane emission during closing hours was ((27.5+21.5)/2 =) 24.5 kg CH_4 h^{-1}. The daily average methane emission was then 25.6 kg CH_4 h^{-1} when considering the plants opening hours during a week.

The daily emission rate of N_2O could only be estimated. The estimation is very uncertain due to the few measurements. The daily average N_2O emission was then 1.85 kg N_2O h^{-1}.

Table 7 provides an overview of emission factors based on the measured emission rates and the treated amount of biowaste and the plant's production of compost and methane (recovered and utilized). The emission rates are compared to the default emission factors provided by the IPCC for biological treatment of solid waste. The IPCC (2006) provides default values for composting and anaerobic digestion, respectively. The IPCC emission factors are given per treated waste input (per kg of wet weight).

Table 7. Overview of average emission factors based on average methane and N_2O emission rates of 25.6 and 1.85 kg h^{-1}, respectively.

Emission factor	**Yearly generation**	**CH_4**	**N_2O**
Emission factor; per kg treated waste material (g/kg waste treated)	45.000 tonne wet weight	5,0	0,4
Emission factor; per kg generated compost (g/kg compost)	18.600 tonne wet weight	12,1	0,9
Emission factor; per kg generated methane (g/kg CH_4 gas recovered and utilized)	$1.32 \cdot 10^6$ m^3 CH_4	238,0	
IPCC emission factors*: Composting (g/kg waste treated)	Wet weight basis	4 (0.03 – 8)	0.3 (0.06 – 0.6)

IPCC emission factors: Anaerobic digestion (g/kg waste treated)	Wet weight basis	1 (0 – 8)	Assumed negligible

IPCC 2006.

6. Conclusion

The emission of methane from Borgstedt was successfully measured using the mobile tracer dispersion method. Emission measurements were conducted over a period of three days. In total 80 plume traverses were successfully obtained. Table 8 shows an overview of the measured emissions. The average methane emissions measured during the three days were 27.5±7.4, 28.5±6.1 and 30.1±11.4 kg CH_4 h^{-1}, respectively.

In general the average emissions measured during the three days were very comparable. However, daily changes in operations of the facility influenced the emission. Turning of the windrows resulted in an increase in methane emission from about 26.3 to 35.9 kg CH_4 h^{-1}. Even though the mechanical turning of the windrows resulted in a significant increase in methane emissions, also lower emissions were observed during the measuring period, which could be due to the lag phase between two turning events. The lowest emission (19.1 kg CH_4 h^{-1}) was measured immediately after the all the windrows has been turned. Lower emissions (21.5 kg CH_4 h^{-1}) were also seen after ended work hours in comparison to emissions measured during the facility's open hours (30.2 kg CH_4 h^{-1}). The results also indicated that leaving the door between the windrow composting area and the hall with the aerobic reactors open after ended work hours resulted in increased emissions.

Important processes resulting in methane emissions were the anaerobic digestion, the aerobic composting and the storage of the compost in windrows. The wind direction on the last measurement day, June 6th, allowed to split the methane plume into two and in this way determine the emissions from two areas of the facility. This gave an emission distribution for methane of 31% from the biofilter and 69% from the open areas (windrows, compost storage, gas storage, etc.).

The nitrous oxide emission was too small for a downwind quantification, but using the ratio to methane obtained by direct on-site measurements from the biofilter and the windrows and unsieved compost storage allowed making an estimate of the whole site nitrous oxide emission. The direct measurements suggested that the main part of the emitted nitrous oxide came from the biofilter. The emission was measured to 1.4 kg N_2O h^{-1} from the biofilter and between 0.3 and 0.6 kg N_2O h^{-1} from the open areas. Also the emission of ammonia was estimated using direct on-site measurements combined with the methane emission results, estimating an NH_3 emission from the biofilter of more than 10.3 kg NH_3 h^{-1} and between 3 and 10 kg NH_3 h^{-1} from the open areas.

Table 8. Overview of measured emissions during the three days measuring campaign.

Date	Measuring time interval	Plume traverses	Methane emission (kg h^{-1})	N_2O emission (kg h^{-1})	NH_3 emission (kg h^{-1})	On-site activities
June 4th	17:50-18:40	7	27.5±7.4	NA	NA	No activities, but door open to aerobic reactor hall
June 5th	11:00-13:30	24	30.2±5.2	NA	NA	Activities, but no turning
	17:00-18:00	6	21.5±4.2	NA	NA	No activities, door closed
June 6th	10:40-12:50	21	26.3±5.5	A: 1.4 B: 0.3 to 0.6	A: 3 to 10 B: >10.3	Activities but no turning
	12:50-14:20	19	35.9±14.1			Activities and turning
	14:20-14:45	3	19.1±0.9			Activities but no turning

7. References

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